ARMY RESEARCH LABORATORY

Ballistic Properties of Zylon for Application to Firearm Projectile Protection

by E. Pineda, C. Hogue, and W. Goldsmith

ARL-CR-529 **July 2003**

prepared by

Department of Mechanical Engineering
University of California, Berkeley
Berkeley, CA 94720

in cooperation with

SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025

under contract

DAAD17-01-P-0888

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Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5066

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Abstract

In recent years, a para-phenylene benzobisoxazole fiber, Zylon (registered trademark of the Toyobo Company), has surfaced as a potential candidate for body armor to possibly replace Kevlar (registered trademark of DuPont). Zylon's effectiveness depends on its ballistic properties as well as its mass in comparison with Kevlar. The present extended investigation focuses on determining the ballistic limit and the V_{50} velocity for 10, 20, and 30 stitched plies of Zylon using standard North Atlantic Treaty Organization 9-mm nonrotating strikers. This report concentrates specifically on the ballistic limit of 10-ply Zylon, as well as the effect that impact location has on perforation. It was also discovered that many other factors affect the ballistic performance, including slip of the fabric in the holder, the preparation of the shell, and the amount of fiber damage present. These aspects will be considered when evaluating Zylon's performance and determining whether or not it is indeed superior to Kevlar for applications in body armor and personnel protection. The first instance of perforation for 10-ply Zylon occurred at an initial velocity of 341.4 m/s, and the highest initial velocity for a ricochet was 566.2 m/s.

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1. Introduction

Zylon[*] is a para-phenylene benzobisoxazole (PBO) fiber made by the Toyobo Company of Osaka, Japan, with promise to replace today's aramids as the super high-performance fiber of the future. It is far superior to Kevlar[†] and other aramids in both mechanical properties and resistance to such environmental effects as heat, moisture, abrasion, and seawater corrosion. Because of these properties, the U.S. Army took an interest in Zylon as a future bulletproof material. Based on a contract from the Army, the goal of this project is to determine the ballistic performance of Zylon. This is summarized into two basic experimental results—the ballistic limit and the limit velocity.

The earliest reference to "modern" body armor located by a literature search consisted of a 1931 photograph of a bulletproof vest that was not published until 1988 [1]. Other references involving personnel protection have appeared primarily during the last decade [e.g., 2–6] and have been almost exclusively concerned with ballistic fabric or fabric composite shielding. Widespread investigations of projectile penetration and perforation for normal impact have been presented in references [7, 8] and for nonstandard impact conditions, in reference [8]. The ballistic limit can be improved in many ways, both through advances in materials and in the geometry of their application. This study involves simply testing a new material, Zylon, for comparison against similar ballistic fabrics such as Kevlar. New applications for Zylon are being investigated, including a joint project between Boeing, SRI, the Federal Aviation Administration, and the University of California, Berkeley, to explore containment barriers on commercial aircraft jet engines. Their function would be to protect vital fuselage components and systems, as well as passengers, from high velocity fan fragments that can result from catastrophic engine failure.

2. Objectives

The ballistic limit represents the speed of a nonrotating striker of given mass and dimensions at which half of the projectiles will just perforate a specified target at normal incidence [9]. The V_{50} and limiting velocity is a somewhat more complicated mathematical function and requires a program to compute. These calculations will be made for the samples of 10-, 20-, and 30-ply Zylon targets. In addition to these concrete objectives, other consequential concerns arose after the initial stages of experimentation. First, it was discovered that the boundary conditions of the Zylon target had a great affect on the performance of the fabric. Not only the velocity of the

[*] Zylon is a registered trademark of the Toyobo Company.
[†] Kevlar is a registered trademark of DuPont.

projectile, but also the location of the impact (relative to the edges of the target holder) became important. This phenomenon is clearly rooted in the "give" of the material farther from its rigid boundaries. The results of a static force deflection test at various locations on the target will be discussed later. At this point, the effects are only qualitative, but there is hope of developing a model (based on the boundary conditions of a thin membrane with a distributed load) to make this conclusion more quantitative. Also, due to the thickness of the target samples, there was slipping of the material within the holder at high/nonperforating shots. Some of this should be eliminated after some modifications to the target holder (see section 5).

3. Experimental Setup

The experimental setup included a 14- × 14-in aluminum target holder, C-clamped at four corners to a steel "backstop" (Figure 1) that was, in turn, secured to a 680-kg steel table on which the gun was mounted.

Figure 1. The aluminum target holder clamped to the steel backstop.

The targets were struck relatively centrally and normally by standard 9-mm full metal jacket flatback handgun projectiles, made by either Remington or Winchester. The projectiles had a nominal diameter of 0.355 in and a length of 0.625 in. They were made of lead, with a thin copper alloy jacket, and had an average mass of 124 gr each and a sectional density of 0.141.

The 9-mm projectiles were saboted for a 0.50-cal. powder gun. The 0.50-cal. powder gun (Figure 2) consisted of a 20-mm-thick high-strength steel barrel with an inside diameter of 0.501 in and a length of 1.6 m, a breech capable of accommodating a 50-mm cartridge and a supporting rail frame which attached the unit to the support.

(a) (b)

Figure 2. The 0.50-cal. powder gun: (a) side view and (b) rear view.

The initial velocity of the projectiles was measured by the duration required to break the beams of two parallel helium-neon lasers positioned directly in front of the muzzle, separated by 165 mm, with the first of the two lasers located 24 in from the gun muzzle. The target itself was ~44 in from the muzzle. The lasers were focused on two custom photodiodes generating a voltage pulse recorded by a Hewlett-Packard 5316 time-interval counter. The final velocity of the fastest object behind the target was determined by the time between the signals generated by two aluminum foil make screens, each about 432 × 254 mm in size, and separated by 155 mm. The two aluminum foil sheets constituting a make screen were separated by a distance of 6 mm. The two make screens generated both a starting and stopping pulse recorded by a second time interval meter from which the final velocity was determined.

A second "backup" system of consecutive paper targets with a grid of interlocking conducting ink lines (Figure 3) worked in a similar fashion to the foil, also making use of a second Hewlett-Packard 5316 time-interval counter.

A blast shield was placed 10 inches in front of the gun muzzle to prevent undue damage to the rebound catcher box and to keep gasses and firing debris from interacting with data-collecting equipment. The rebound catcher box (Figure 4) was essentially a foam cage with an entrance hole for the projectile and small holes in the sides for the initial velocity lasers to pass through to the detectors. A catcher box using rags was placed behind the gun table to soft recover projectiles and plugs. Several blocks of buff potters clay were placed in front of this catcher box to further slow perforating projectiles.

(a) (b)

Figure 3. Timing grid holders: (a) 3/4 view from ~2 m and (b) top view, close-up.

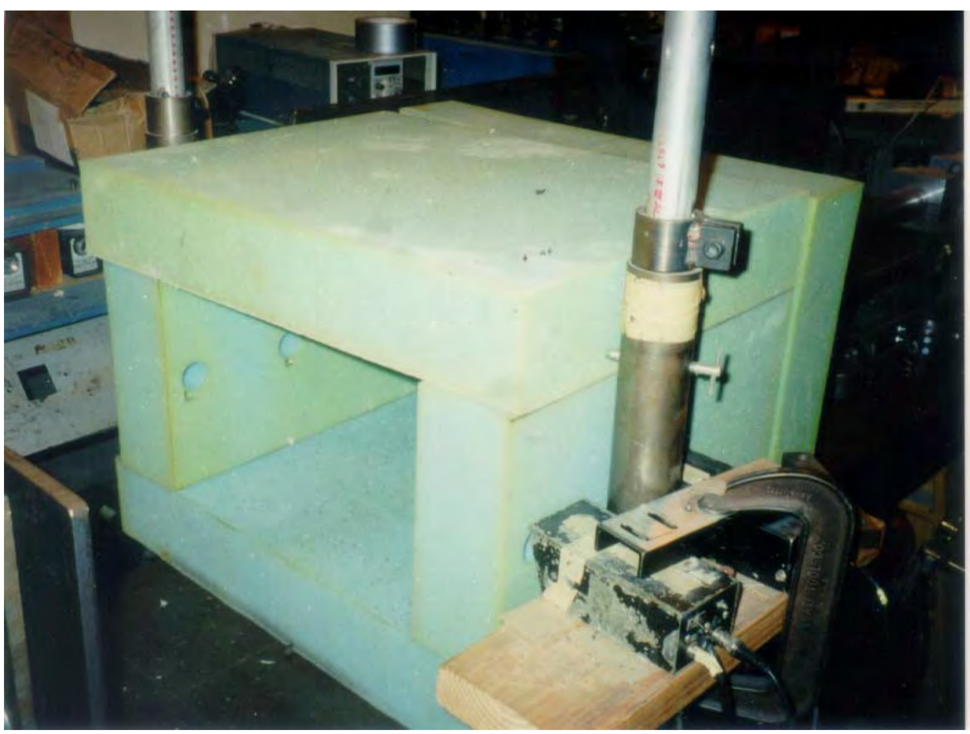


Figure 4. Rebound catcher box.

4. Procedure

The 12- × 12-in Zylon target sample (Figure 5) was secured in an aluminum target holder with essentially a machined "tongue and groove" system to minimize fabric slipping. Uniformity is achieved through the use of an 85 in-lb torque wrench at the numerous screws around the target holder. The targets themselves are 10-, 20-, and 30-ply sheets of Zylon sewn together with chain-link fence-type crisscross stitching. For the thicker samples, the tapped holes will be bored out, and stronger tool-grade steel bolts will be used in lieu of the less reliable lag screws. The desired impact location was aligned to the bore by a laser placed in the breech. The position of the impact was recorded to investigate effects of different tensile preloads in the Zylon target.

Figure 5. Zylon target (note: 20-ply sheet shown).

The lasers and photodiodes were turned on to record the initial velocity of the striker upon beam interruption. Two aluminum foil make switches, each consisting of a set of closely spaced parallel sheets, were connected to a time-interval meter that measured the time differential of the passage between the two positions, representing the final velocity of the projectile behind the target.

Following a test, the projectile was recovered. In a few instances, the projectile shattered, most likely from contact with metallic objects other than the target (e.g., the back of the steel catcher box), and, in other cases, it could not be recovered due to single or multiple ricochet, especially when deviating from its initial trajectory due to impact. The position of the holes in the foils was examined to ascertain the projectile trajectory.

5. Results and Discussion

5.1 Sources of Error

There are many factors that contribute to the accuracy of our data; all must be taken into account when observing the data. First and foremost are the boundary conditions of the target holder. The closer to an edge or corner the projectile strikes, the easier it is for the projectile to perforate. With multiple shots per target, it is impossible to have all shots in the center. Another concern when firing multiple shots per target is whether or not the strength of the target as a whole is compromised after the first shot. Figure 6 shows the typical target deformation (originally taut) from a near-perforating target-center shot. If a shot hits too close to a previous impact, the projectile may strike fibers damaged from a previous shot. It is obvious that if this is the case, the data obtained will not be accurate.

The way that the target is secured in the holder also affects the outcome of shots. The target slips slightly from the "grasp" of the target holder upon impact, which increases the targets resistance to perforations. The amount the target slips ranges from 1/2 to 1 in. Previously, the target holder used 16 tapped holes with bolts torqued to a maximum of 85 in-lb to secure the target. Any torque higher than 85 in-lb would snap the bolts. Also, after a few months, the threads of the holes began to wear. This created a resistance to the torque applied in the bolts which made it difficult to assess the actual torque in each bolt. The target holder has been modified to a nut and bolt design, which allows for more torque to be applied to each bolt, and there is no resistance from threads. Soon, higher-grade, larger diameter (3/8 in rather than 1/4 in) bolts will be used, allowing for even more torque.

The way that a shell is loaded can also have a great impact on the projectile's initial velocity. Due to the size of the projectiles, slight variations in the amount of wadding or the way it is tamped down in the shell can greatly affect velocity. It is difficult to obtain desired velocities, and thus difficult to get data for specific areas of interest. This proves to be quite a nuisance when specific velocities are needed to find the V_{50} or the ballistic limit. It becomes a "shooting-in-the-dark" process, which increases the number of targets needed to obtain specific data.

Figure 6. Typical target deformation of a near-perforating shot.

5.2 Load-Deformation Tests

Due to the implication that the location of impact (with respect to the boundary of the target holder) may greatly affect the chance of perforation, load-deformation tests were performed on a 10-ply sheet of Zylon while it was secured in the target holder. Each of the 16 screws was torqued up to 85 in-lb. Figure 7 shows these tests that were performed at three locations—2.5 in, 4.5 in along the diagonal, and in the center.

It was found that the closer to the center of the target one gets, the less force is required to elastically deform the material. Therefore, shots fired closer to the corners have a greater chance of perforating because less energy is absorbed by the target. This fact greatly affects our ballistic results. It was also found that when a target is fired, it slips in the target holder. Due to this implication, we changed the target holder to accommodate a nut and bolt setup with high-grade bolts.

6. Ballistic Tests

Fifty-four shots were fired at various points on 10-ply sheets of Zylon. The complete results for all the shots, obtained from the data in Table 1, are shown in Figure 8. However, since the location of the shots, as well as many other factors, affects the projectile's ability to perforate, Figure 8 is not a completely accurate depiction of the ballistic capabilities of Zylon. However,

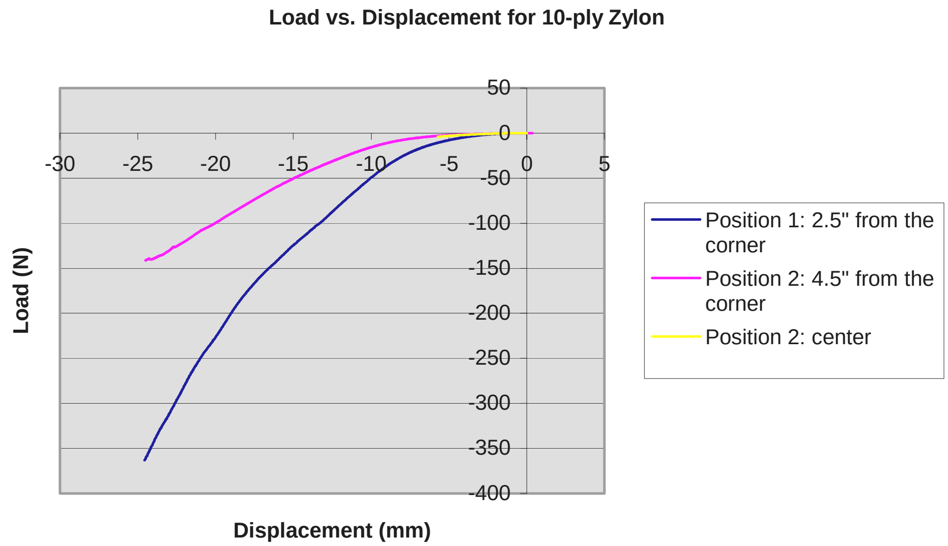


Figure 7. Load displacement curves.

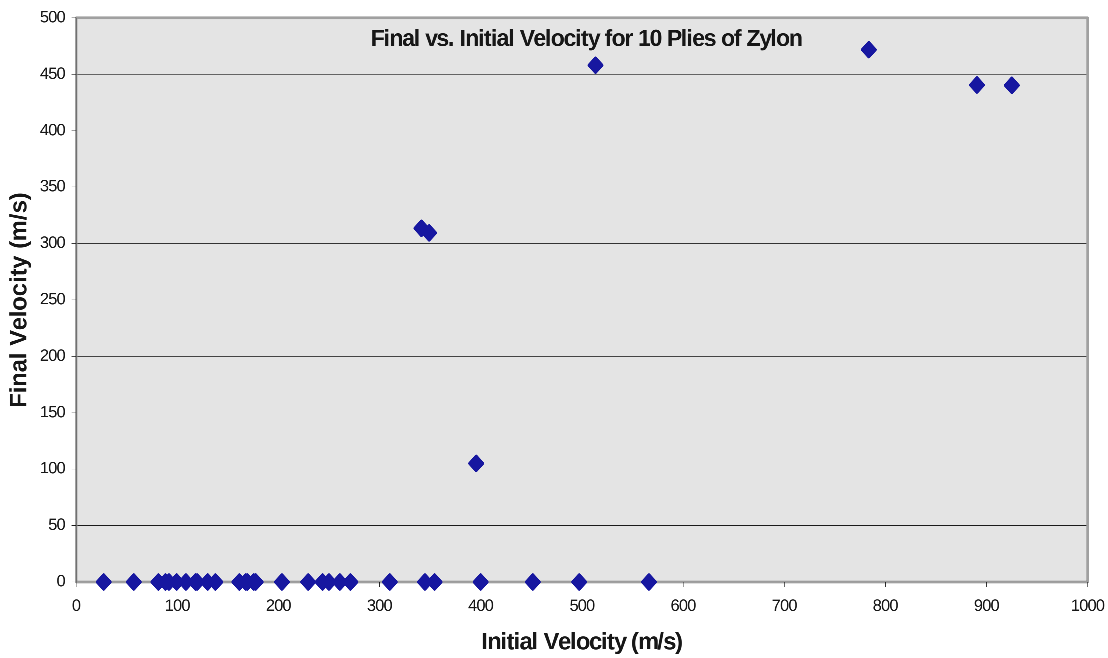


Figure 8. Final vs. initial velocity.

corner shots can be considered a lower bound of sorts and the center shots an upper bound. These discrepancies can be clearly seen using Figure 8. For instance, there is a nonperforating shot with an initial velocity of 566 m/s fired at the center as well as a perforating shot at 349 m/s fired near the corner. Finally, Figure 9 is a three-dimensional plot of initial velocity of projectiles vs. the striking location on the target measured from an origin at an arbitrary corner of the target.

Table 1. Tabular ballistic data.

Shot No.	Ply	Powder Load (g)	Initial Velocity (m/s)	Final Velocity (m/s)	Type of Bullet	Perforation?	X Position (in)	Y Position (in)	Comments
1	10	5.2	error	NA	R	N	3.25	9	
2	10	5.81	348.9	309.5	R	Y	7	8.25	
3	10	6	error	508.86	R	Y	4	4	
4	10	6	890.4	440.5	R	Y	7.5	4.5	
5	10	6	320.5	error	R	Y	6.375	8.125	Shot fired without sabot stripper.
6	10	6	783.5	471.8	R	Y	5.25	3.5	Shot fired without sabot stripper.
7	10	6.5	598.7	error	R	Y	4.5	4.75	Sabot was not stripped.
8	10	6.5	513.4	458.2	R	Y	3.25	3.75	
9	10	7	error	457.8	R	Y	5	3.75	
10	10	7	error	error	R	Y	8.125	4.5	
11	10	7	591.2	error	R	Y	9.75	7.25	
12	10	7.5	395.3	105	R	Y	6.375	7.5	
13	10	7.5	1757.2	error	R	Y	3.5	7.875	
14	10	8	error	236.6	R	Y	3.875	6.25	
15	10	5	682.4	error	R	Y	7.875	6.75	
16	10	0.5	91.63	NA	R	N	8.25	4.75	
17	10	0.75	error	NA	R	N	6	6.125	
18	10	0.75	81.45	NA	R	N	3.25	4.125	
19	10	1	27.3	NA	R	N	6.125	8.375	
20	10	1	88.33	NA	R	N	3	7.5	
21	10	1.25	175.53	NA	R	N	5.625	4.25	
22	10	1.5	19.55	NA	R	N	8	8.75	
23	10	1.75	error	NA	R	N	7.75	6.375	
24	10	1.75	118	NA	R	N	4	3.75	
25	10	6	924.89	440.22	R	Y	7.25	5.75	
26	10	0.5	error	NA	W	N	4.375	4.875	
27	10	0.5	56.99	NA	W	N	7.75	7.25	
28	10	0.75	99.4	NA	W	N	6.875	6.125	
29	10	1	108.4	NA	W	N	4.75	8	
30	10	1.25	167.67	NA	W	N	4.125	4.5	
31	10	2	130	NA	R	N	2.75	8.875	
32	10	2.5	137.5	NA	R	N	7.625	3.75	
33	10	3	error	NA	R	N	5.75	6.125	
34	10	3.5	354.3	NA	R	N	2.5	4.25	
35	10	1.5	error	NA	W	N	5.5	NA	

Table 1. Tabular ballistic data (continued).

Shot No.	Ply	Powder Load (g)	Initial Velocity (m/s)	Final Velocity (m/s)	Type of Bullet	Perforation?	X Position (in)	Y Position (in)	Comments
36	10	1.5	260.6	NA	W	N	2.5	3	Sabot was not stripped.
37	10	2.5	229.26	NA	W	N	4	8.25	
38	10	2	169.3	NA	W	N	4	8.125	
39	10	3	161.29	NA	W	N	8.25	7.5	
40	10	3.5	310	NA	W	N	4.375	5.5	
41	10	4	497.4	NA	R	N	8.375	4.125	Bullet hit target holder before striking target.
42	10	4	243.5	NA	R	N	6.875	4.5	
43	10	4.5	451.44	4.5	R	N	4.875	6.25	
44	10	5	342.89	error	R	Y	3.5	6.375	
45	10	3	344.9	NA	R	N	5.25	4.25	
46	10	3.5	203.5	NA	R	N	3.625	5	Sabot was not stripped.
47	10	4	error	error	R	error	NA	NA	
48	10	3.5	566.2	NA	R	N	5	6.5	
49	10	3.6	399.8	NA	R	N	5.75	6.25	
50	10	3.7	error	error	R	error	NA	NA	
51	10	4.1	250	NA	R	N	5.5	5	Initial velocity obtained from high-speed video camera.
52	10	4.2	341.4	313.6	R	Y	5.5	5.75	
53	10	4	177.4	NA	R	N	6.125	6	
54	10	4	271.1	NA	R	N	5.5	6	

Some interesting information was gained from the recovered projectiles themselves. Figure 10a shows some typical low-velocity, nonperforating projectiles (57–138 m/s) that suffered almost no visible damage upon impact. However, it is also known that each of these projectiles rotated upon impact with the Zylon target and was finally brought to rest completely sideways. This was inferred from the imprint of the bullet left on the Zylon, clearly showing the bullet-like profile of the projectile, rather than a circular one. The extreme case of this rotation can be seen in Figure 10b. Here, higher velocity nonperforating projectiles (161–451 m/s) showed significant deformation in the lateral direction from being "squished" sideways against the Zylon target upon rotation. (Note: The bullets in Figure 10b are shown from behind, parallel to their major axes.) This rotation appears to help the target absorb energy, thus allowing no perforation at 451 m/s, even though lower velocity projectiles showed perforation (such as the 321- and 349-m/s projectile in Figure 10d). Compare these laterally deformed projectiles to those in Figure 10c. Here, the projectiles did not rotate upon impact, and they bear the more intuitive

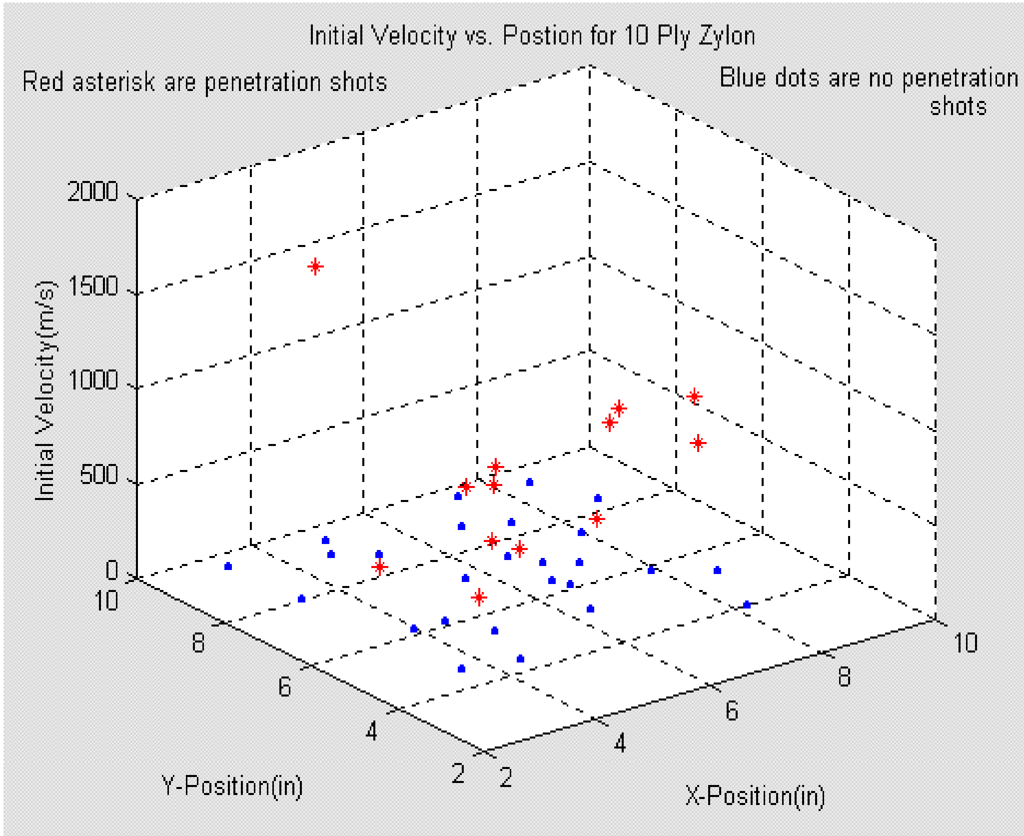


Figure 9. Final vs. initial velocity (striking velocity).

"snub-nosed" shape expected from fully anterior deceleration. Finally, Figure 10d shows some typical perforating shots with velocities ranging from 321 to 890 m/s. It is interesting to note that the higher velocity perforating shots show less damage than those that perforated at lower velocity.

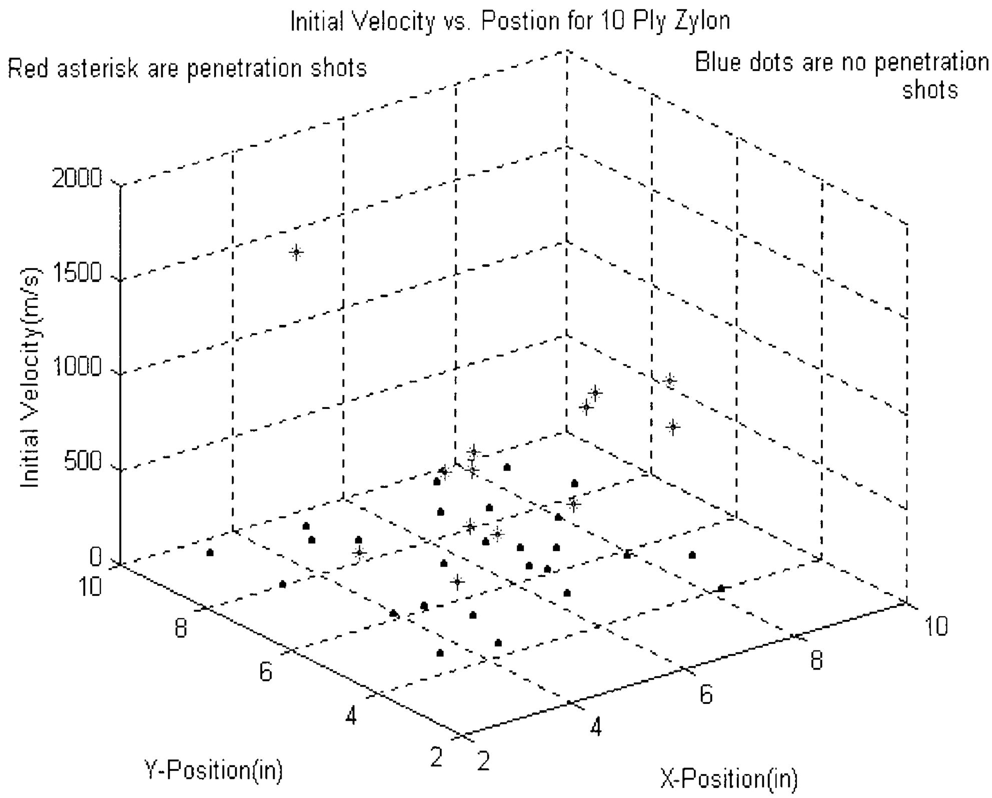
The V_{50} was estimated using the following:

$$V_{50} = V^{*}(a_o + a_1X + a_2X^2 + a_3X^3 + a_4X^4), \tag{1}$$

where $X = A_dA_p/m_p$ = (fabric areal density)(projectile base area)/(projectile mass),

A_d = 1.56 kg/m^2, A_p = 254.5 × 10^{-6}kg/m^2, m_p = 0.00803 kg, and a_o = 0.323, a_1 = 6.732, a_2 = !26.642, a_3 = 68.442, a_4 = !62.446, and V^* = 813.2 [10].

V_{50} was calculated to be 486.8 m/s. Our first instance of perforation was at 341.4 m/s, and our last instance of no perforation was at an initial velocity of 566.2 m/s. Both of these shots were center shots, but the former shot was fired after the nut and bolt fasteners were implemented in the target holder. This allowed for a reduction in slip, thus allowing the target to absorb less of



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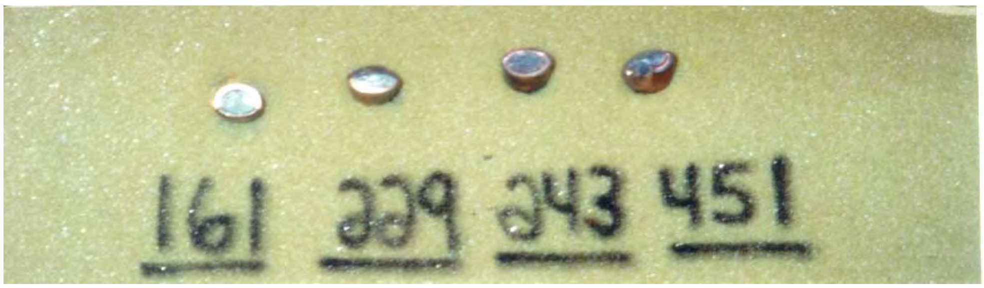
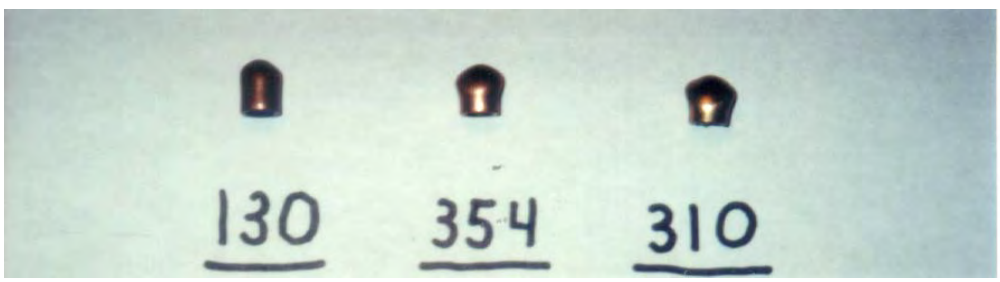
(a)



(b)



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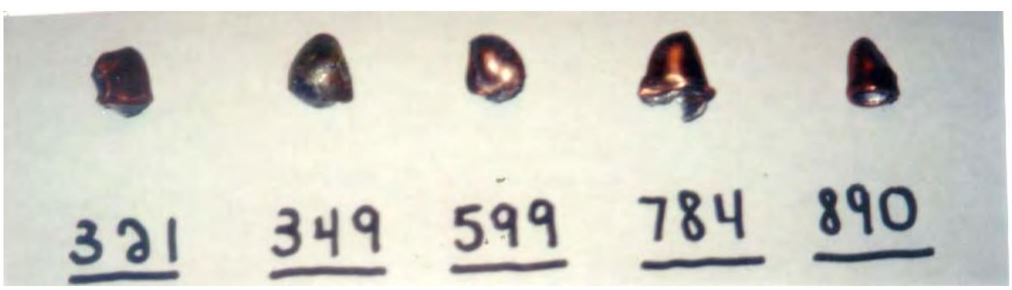

(d)

Figure 10. Recovered projectiles (note: numbers beneath projectiles indicate initial velocity in meters per second).

the projectile's kinetic energy, resulting in a perforation. These variances in actual limits from the theoretical limit can be attributed to the location of the shots, the accuracy of the initial velocity equipment, and slipping in the target holder. None of these factors can be completely eliminated. Multiple shots per target are necessary due to the number of targets available. The slip can be reduced in our target holder, but it can never be zero. With the data provided in this report, the ballistic limit for various impact locations can be determined. However, the ballistic limit is not the same as the V_{50} or the limiting velocity. The V_{50} as well as the limiting velocity will be found on a later date using the programs provided.

The average 9-mm handgun has a muzzle velocity of 388 m/s [11]. Ten plies of Zylon are not enough to stop a shot from the average 9-mm handgun, but a slight increase in the number of plies should prove effective. Ten plies of Kevlar 29 have a V_{50} of 434 m/s [12]. Although Kevlar 29 has a higher V_{50} than Zylon, Zylon has a lower areal density. Ten plies of Zylon have an areal density at 1.56 kg/m^2, and 10 plies of Kevlar 29 have an areal density of 2.95 kg/m^2 [12]. Therefore, it may take more plies of Zylon than Kevlar 29 to stop a projectile, but with Zylon's significantly lower areal density, that amount of plies will weigh less than the ballistic equivalent made of Kevlar 29. This shows that Zylon would be more practical than Kevlar 29 for use as body armor in the military and law enforcement where mass is critical.

7. Conclusions

Ten plies of Zylon were not enough to stop a 9-mm bullet fired from an average handgun, nor was the theoretical V_{50} or the ballistic limit higher than that of Kevlar 29. However, a slight increase in plies should be enough to overcome both of these. Since Zylon has a far less areal density than Kevlar 29, the mass of the number of plies needed to reach the ballistic limit of Kevlar would still be less than that of 10 plies of Kevlar. Twenty plies of Zylon, which will be tested next, should prove effective against projectiles fired at 388 m/s.

Despite the sources of error, a ballistic curve was obtained. The error that comes from the target and the target holder can be considered positive because Zylon in real-world use will not be in laboratory conditions. For 20 plies of Zylon, the slip will be minimized due to modifications made on the target holder. It is essential that the fabric holds up no matter what adversities it faces—multiple shots, slipping, or any other nonideal conditions.

Zylon is the "ballistic fabric" of the future. Zylon's low areal density allows for more maneuverability and proves to be more practical for applications in the armed forces and law enforcement than Kevlar. Further testing will show the number of plies of Zylon needed to achieve the same ballistic limit, as Kevlar 29, will weigh less.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
July 2003	Interim	August 2001–April 2002

4. TITLE AND SUBTITLE

Ballistic Properties of Zylon for Application to Firearm Projectile Protection

5a. CONTRACT NUMBER

DAAD17-01-P-0888

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

PERS01

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WM-TD
Aberdeen Proving Ground, MD 21005-5066

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

ARL-CR-529

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

In recent years, a para-phenylene benzobisoxazole fiber, Zylon (registered trademark of the Toyobo Company) has surfaced as a potential candidate for body armor to possibly replace Kevlar (registered trademark of DuPont). Zylon's effectiveness depends on its ballistic properties as well as its mass in comparison with Kevlar. The present extended investigation focuses on determining the ballistic limit and the V_{50} velocity for 10, 20, and 30 stitched plies of Zylon using standard North Atlantic Treaty Organization 9-mm nonrotating strikers. This report concentrates specifically on the ballistic limit of 10-ply Zylon, as well as the effect that impact location has on perforation. It was also discovered that many other factors affect the ballistic performance, including slip of the fabric in the holder, the preparation of the shell, and the amount of fiber damage present. These aspects will be considered when evaluating Zylon's performance and determining whether or not it is indeed superior to Kevlar for applications in body armor and personnel protection. The first instance of perforation for 10-ply Zylon occurred at an initial velocity of 341.4 m/s, and the highest initial velocity for a ricochet was 566.2 m/s.

15. SUBJECT TERMS

Zylon, body armor, ballistics, ballistic testing

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Nevin Rupert
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	24	**19b. TELEPHONE NUMBER** (*Include area code*) (410) 278-9652

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